AUTOMATIC CONTROL OF WATER COOLED SUITS FROM DIFFERENTIAL TEMPERATURE MEASUREMENTS

by Samuel J. Troutman, Jr., and Paul Webb, M.D.

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SUMMARY

An automatic controller based on temperature changes (ΔT controller) was designed to regulate the temperature of water used to cool a man doing treadmill work while wearing a water cooled clothing assembly. Inputs to the ΔT controller were: a) the difference between suit inlet and suit outlet water temperature (heat removal rate at fixed water flow); and b) four selected skin temperatures.

Experiments were conducted to establish the correct weighting and damping factors for smooth and accurate control. Further experiments evaluated the ΔT controller during quiet periods, during steady work at a moderate level, and during intermittent work. Long term accuracy and stability were established during a final experiment lasting 16 hours, in which the subject slept, ate meals, worked, and rested.

The advantages of the ΔT controller are that it provides relief from the responsibility for regulating one's own thermal state; guarantees low sweat rates and no dehydration at the same time as it prevents chilling and discomfort; provides maximum heat removal and minimum heat storage; and gives good long term stability at low metabolic levels.

INTRODUCTION

The metabolic heat of thermally isolated men can easily be removed by water cooling. So powerful is this mechanism that men can be overcooled even at high rates of activity, as reported previously from our laboratory (ref. 6 and 7). When a man is overcooled, discomfort and vasoconstriction may occur. When the cooling potential is insufficient, sweating can occur. Control of cooling is a basic requirement in the prevention of physiological strain.

Control of water cooling should be natural, timely, and accurate with respect to the need for heat removal. Control can be either manual, when the subject selects the temperature of the cooling water in response to his own sense of thermal comfort, or automatic, based on physiological responses related to the need for heat removal. Manual control has been tried in several laboratories (ref. 1, 2, 4, 5, and 8); however it became apparent that the subject was a poor judge of his own thermal state in that he tended to lag or lead his requirement for cooling, and possibly found himself preoccupied with control. In our laboratory we have previously demonstrated one approach to automatic control based on an oxygen consumption input (ref. 7), and it appeared to be an advantageous alternative to manual control. In the work reported here, another type of controller was designed and evaluated experimentally. It was an automatic closed loop controller which used temperature inputs only--a differential temperature which varied with the heat removal rate and the response of selected skin temperatures.

This work was carried out under contract with the Electronics Research Center, N. A. S. A., as part of the program of its Instrumentation Laboratory. The differential temperature controller ("ΔT controller") was expected to advance the art of automatic control of water cooling garments both by using skin temperatures as a feedback to close the control loop, and by controlling from inputs that are easily and reliably measured during EVA operations.

The analytical process which led to the development and design of the ΔT controller will be described, along with experiments which verified the ability of the controller to respond correctly to resting and working levels of heat production.

MODEL STUDY

The biothermal responses of a man working in a water cooled garment under continuous manual control by an observer were studied three years ago and the results report by Webb and Annis (ref. 6). As a result of this study, a mathematical model was developed which described the thermal states and heat flows of a man in a water cooled suit (Webb, Annis, and Troutman, ref. 7). In the present study we were interested first in how the postulated ΔT controller would control the model.

In reviewing existing data and our biothermal model, certain input-output relationships became obvious--those of the heat removal rate (H) and the mean skin temperature ($\bar{T}_s$) responses to the inlet water temperature (T_{wi}). It was postulated that control of the suit inlet water temperature, which is responsible for the cooling potential, could be realized from these two informative responses related to heat production.

The control concept was expressed in the following logic statements:

1. at rest, T_{wi}, $\bar{T}_s$, and H are constants;
2. as man goes to work, $\bar{T}_s$ and H will increase if T_{wi} is held constant;
3. as control action lowers T_{wi}, H will continue to increase and $\bar{T}_s$ will decrease until the system seeks to stabilize.

System stability is directly related to the physiological responses to water cooling, that is: undercooling results in a $\bar{T}_s$ that is too high for the associated H, thus driving T_{wi} lower; conversely, overcooling will cause vasoconstruction, a reduction in H, and a lowering of $\bar{T}_s$, even though the metabolic rate remains high, thus allowing T_{wi} to increase. Therefore the control strategy would be that the higher the heat removal rate the lower the water inlet temperature should be, as long as the mean skin temperature stayed within specified ranges.

The development of a ΔT controller depended on establishing a relationship between H, $\bar{T}_s$, and T_{wi} that provided stable and dynamic control of the water coolant in phase with the need for heat removal. The dynamics of the system were neglected initially in order that a simple mathematical statement could be found which would predict the correct steady state conditions. So that this equation would be versatile with respect to initial conditions, the concept of ΔT was developed such that all parameters could be directly or indirectly related to their original state. The following expression resulted:

$$T_{wi} = T_{wi_0} - \frac{\alpha}{\dot{m}c}(H - H_0) - \beta(\bar{T}_s - \bar{T}_{s_0}) \tag{1}$$

where:

T_{wi} = inlet water temperature

T_{wi_0} = initial resting inlet water temperature

H_0 = heat removal rate at rest

H = heat removal rate for any given activity level

$\bar{T}_{s0}$ = resting mean skin temperature

$\bar{T}_s$ = mean skin temperature for any given activity level

$\dot{m}c$ = mass conductivity of the coolant

α = proportionality constant for H

β = proportionality constant for $\bar{T}_s$

The proportionality constants were determined by the substitution of known steady state values for T_{wi}, T_s, and H in the above expression and repeating simultaneous solutions until values were obtained which reasonably predicted T_{wi} for four activity levels ranging from rest to 15 kcal/min (see Figure 1). Although it is recognized that these values are not actually constants, previous use of the biothermal model (ref. 7) demonstrated that such linearization is justifiable. These values are:

$\alpha = 9.27$

$\beta = 5.18$

based on the assumption that T_{wi} is the dependent variable and H and $\bar{T}_s$ are the independent variables.

System dynamics had to be considered on the basis of observed physiological time constants, both in our model studies and in our experimental data. Since the mean skin temperature response was driven by both the man and the water coolant, any further manipulation of its response did not seem justified. However, the heat removal rate demonstrated a fairly consistent response time to changing heat production levels which was directly related to the ideal response of T_{wi}. Using the dynamics of H, Equation (1) was rewritten:

$$T_{wi} = [T_{wi_0} + \frac{\alpha}{\dot{m}c} H_0 - \beta(\bar{T}_s - \bar{T}_{s_0})] - \frac{\alpha}{\dot{m}c} H \tag{2}$$

H was defined as: $H = -\tau\dot{H} + \phi\,(RM + \Delta M)$ (3)

M

Leg -- T_l

M	est.	sim.
Rest	35.5	35.5
5 kcal/min	38.5	39.2
10 kcal/min	40.0	39.4
15 kcal/min	40.5	40.3

Rectal -- T_{re}

M	exp.	sim.
Rest	37.1	37.1
5 kcal/min	37.8	37.8
10 kcal/min	38.5	38.3
15 kcal/min	39.7	38.7

Skin -- $\bar{T}_s$

M	exp.	sim.
Rest	33.3	33.3
5 kcal/min	31.7	31.9
10 kcal/min	30.1	30.7
15 kcal/min	28.7	29.4

Water -- T_{wi}

M	exp.	sim.
Rest	31.3	31.3
5 kcal/min	23.0	23.6
10 kcal/min	17.0	16.2
15 kcal/min	10.0	9.2

H

M	exp.	sim.
Rest	1.4	1.4
5 kcal/min	3.9	3.8
10 kcal/min	6.0	6.0
15 kcal/min	8.5	8.4

Figure 1. Comparison of experimental (exp.) and simulation (sim.) values for equilibria at rest and at three levels of work. In the leg, we estimated (est.) the temperatures to be expected from data in the physiological literature.

where: τ = the time constant of the response of H

ϕ = the proportionality constant relating H and M

RM = the resting heat production rate (resting metabolic rate)

ΔM = the change in heat production rate

The value of τ was assumed to be identical to the time constant of the ideal response of T_{wi}, whereas ϕ was determined by solving Equation (3) at known steady state conditions until a mean value was established that would satisfy the expression with reasonable accuracy. These values were:

ϕ = 0.68

τ = 10 minutes

Equations (2) and (3) were scaled with respect to magnitude by dividing both sides of each equation by 5; then they were mechanized on an analog computer (TR-20, Electronic Associates, Inc.), replacing the T_{wi} generator in the original biothermal model. The analog diagram for the model controller is given in Figure 2.

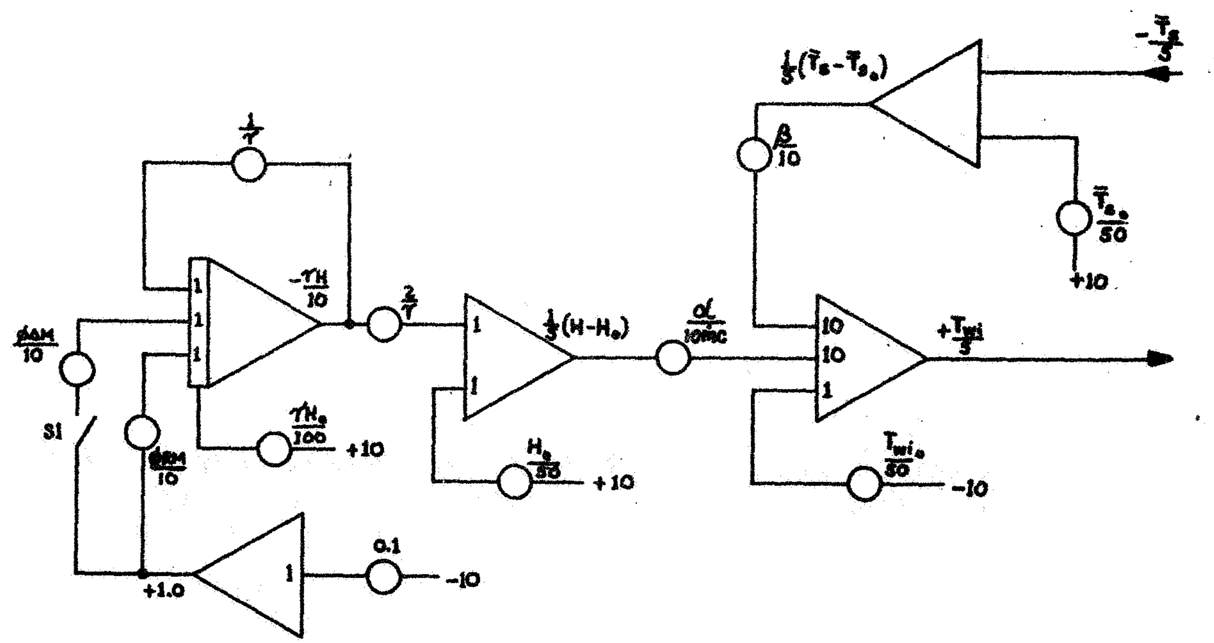

Figure 2. Computer diagram of the model controller.

Two TR-20's were required, one for the controller, the second for the biothermal model.* They were slaved together so that the operation of the complete model would have the proper phase relationship. Simulations of going from rest to three levels of work demonstrated the dynamics of the model with this control concept. The levels of work were 5 kcal/min, 10 kcal/min, and 15 kcal/min. We recorded the transient and steady state responses of compartment temperatures, T_{wi}, and H to compare against experimental data. The duration of each simulation was 5 hours, thus allowing some estimate of long term stability. The computer simulation curves are shown in Figures 3, 4, and 5.

In general the model controller performed reasonably accurately. More physiological insight and more biothermal model complexity would be needed to increase predictability significantly with respect to the experimental data. Better knowledge of the response times of $\bar{T}_s$ and of metabolic heat production, and their interrelationship in a water cooled environment, is of primary importance if control techniques of this type are to be advanced.

DESIGN OF THE EXPERIMENTAL ΔT CONTROLLER

The design of the experimental controller was based on the same control logic used to develop the model controller. A TR-20 analog computer was used to mechanize the controller from the standpoint of logic and signal conditioning. The output of the controller, or analog of T_{wi}, provided a control signal for the cooler located in the water cooling loop. This control signal established both static and dynamic control of the inlet water temperature. Inputs were H and average control skin temperature ($\bar{T}_{cs}$).

Controller Inputs

Measurement of the heat removal rate from the suit (H) was accomplished with a Wheatstone bridge modified to provide weighting factors and variable time integration to the output magnitude and response. In the bridge were thermistor probes (Yellow Springs Instrument Co., type 423), one for the inlet and one for the outlet water temperature; the difference in their temperatures provided a dynamic analog signal proportional to the heat removal rate. Time integration was used to prevent a transient response in the heat removal from overdriving the controller, and to provide an instantaneous average of the heat being removed from the suit by the water coolant. This input was amplified and conditioned to develop the correct relationship to the controller logic.

* A special note of thanks is due to the Cleveland office of Electronic Associates, Inc. for their assistance in making available an additional TR-20 computer.

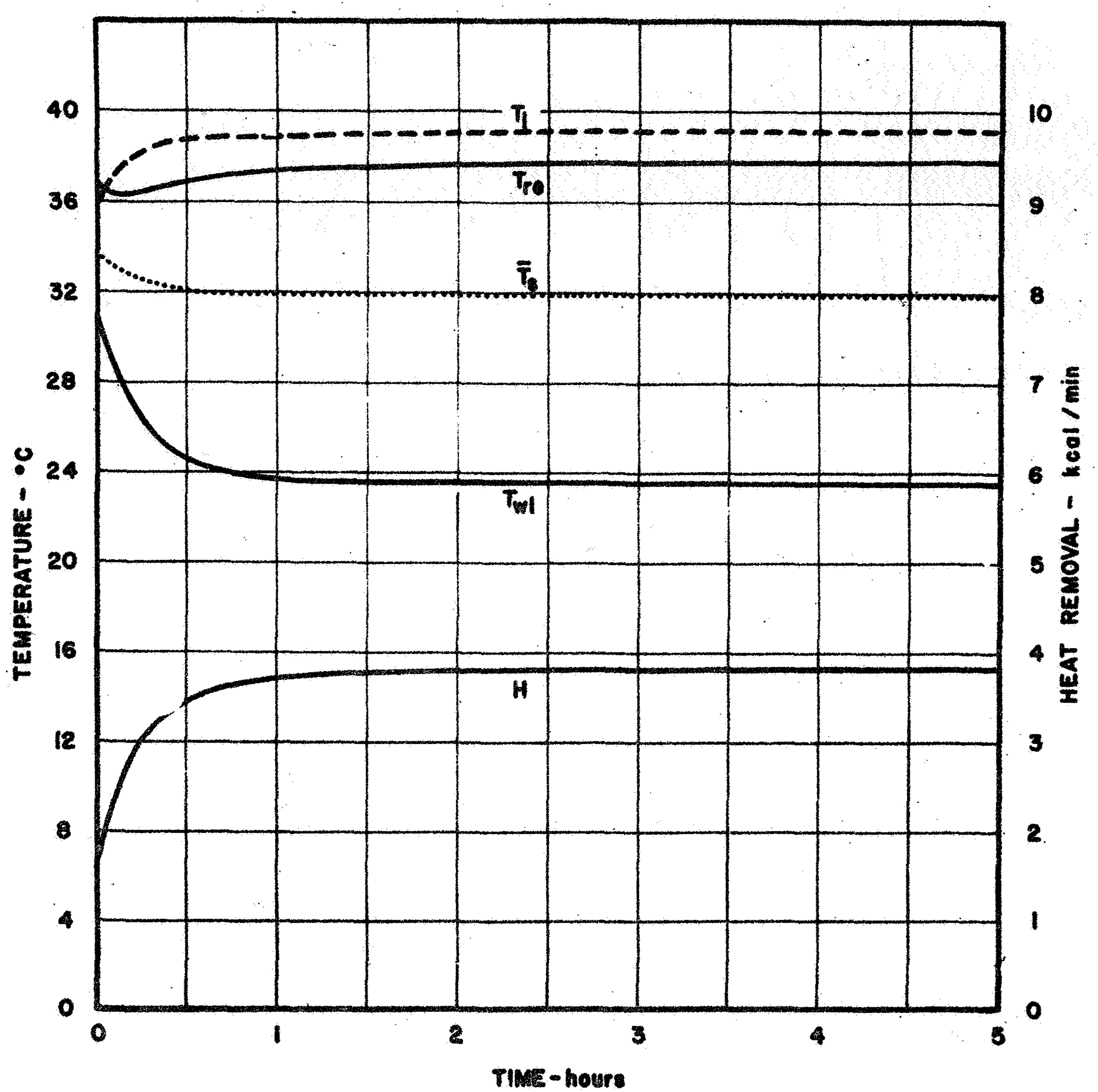

Figure 3. Simulation curves for temperatures in the compartments of the biothermal model, heat removal, and inlet water temperature at M=5 kcal/min.

Using mean skin temperatures derived from many individual measurements was undesirable from a flight operations standpoint; therefore analysis of the individual skin temperature data observed during earlier studies was conducted in an effort to reduce the number of individual measurements and still establish a skin temperature that would provide the necessary control information. This analysis identified four skin temperatures that related to activity levels when averaged. These four skin temperatures were selected as control inputs. Two of them were located over active muscles, right calf and left biceps, and the remaining two points were on the trunk, one over the

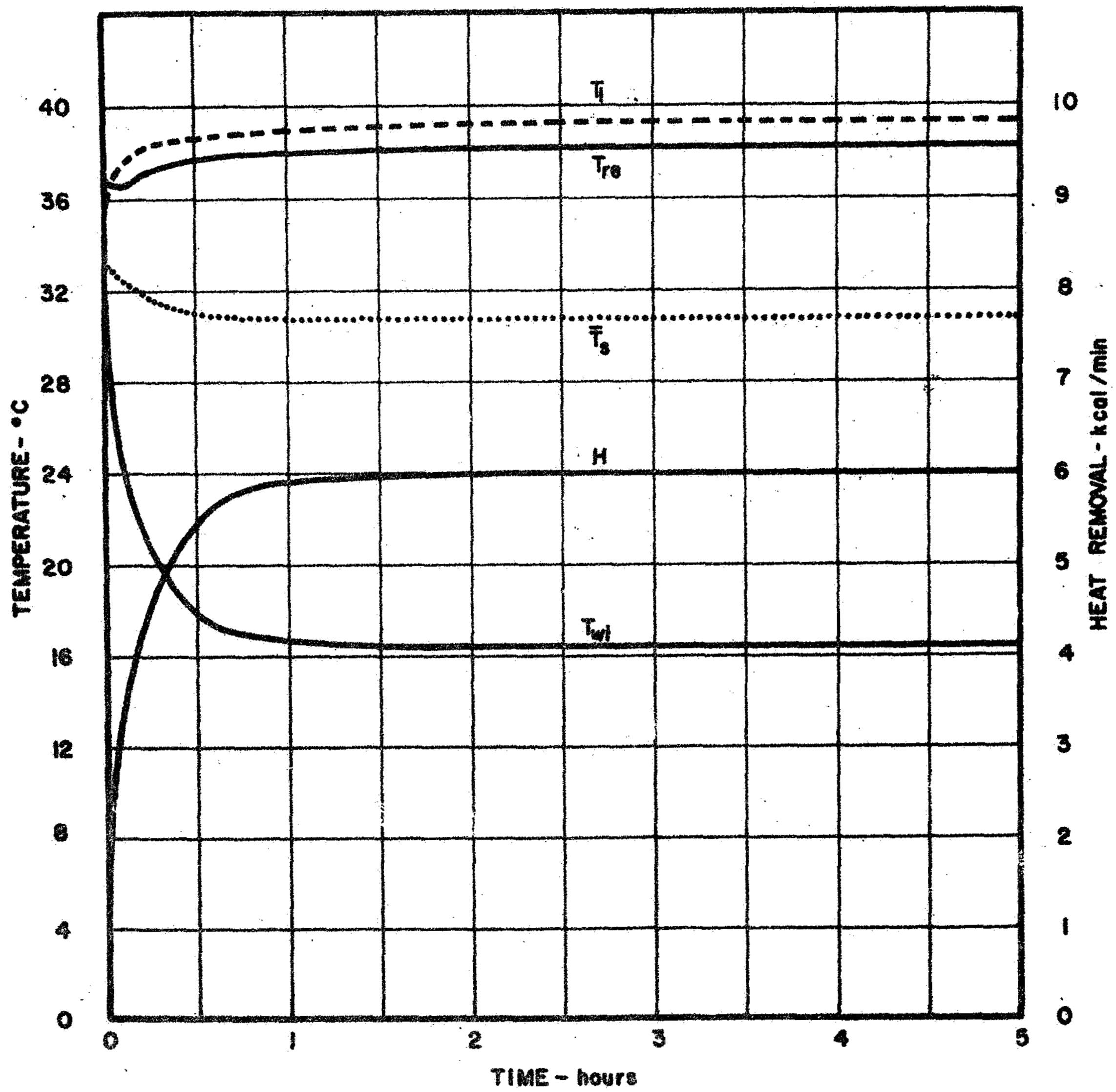

Figure 4. Model simulation curves for biothermal compartments, heat removal, and inlet water temperature at M = 10 kcal/min.

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right kidney and one on the right lower abdomen. It was determined by analysis that when correct cooling was applied for a given level of activity, the average of these four temperatures responded much like the mean of 16 skin temperatures.

These four control skin temperatures (T_{cs}) were measured by thermistor probes (Yellow Springs Instrument Co., type 409) installed in the water cooling suit assembly. The location of these probes on the man is shown in Figure 6. An average control skin temperature ($\bar{T}_{cs}$) was obtained by a

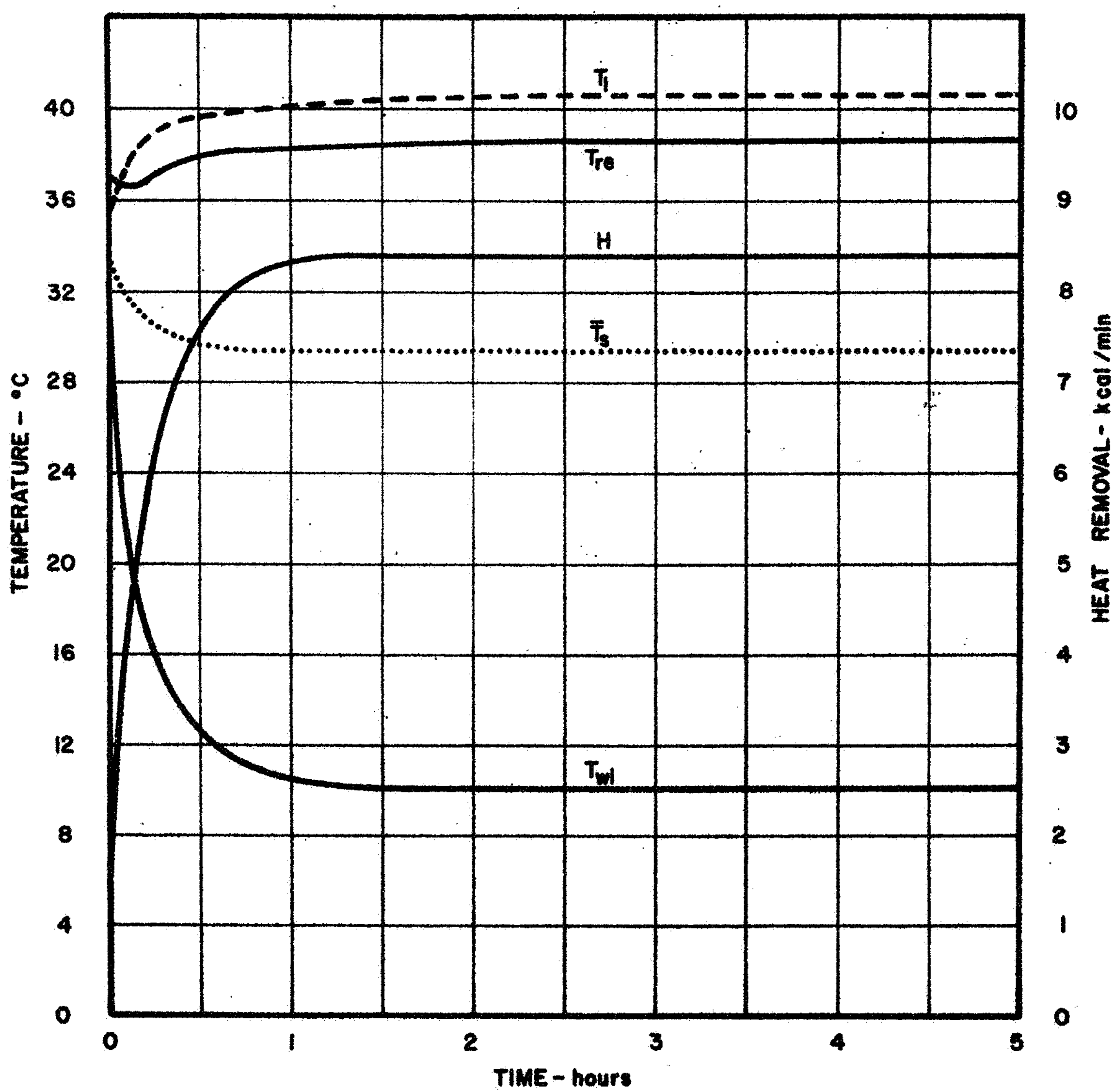

Figure 5. Model simulation curves for biothermal compartments, heat removal, and inlet water temperature at M = 15 kcal/min.

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simple series-parallel network (Figure 7), and since the probes are resistive, their equivalent resistance was used to form a voltage divider circuit which provided a voltage signal proportional to the equivalent change in $\bar{T}_{cs}$. This voltage analog was amplified and weighted to be compatible with the control constants and signal levels.

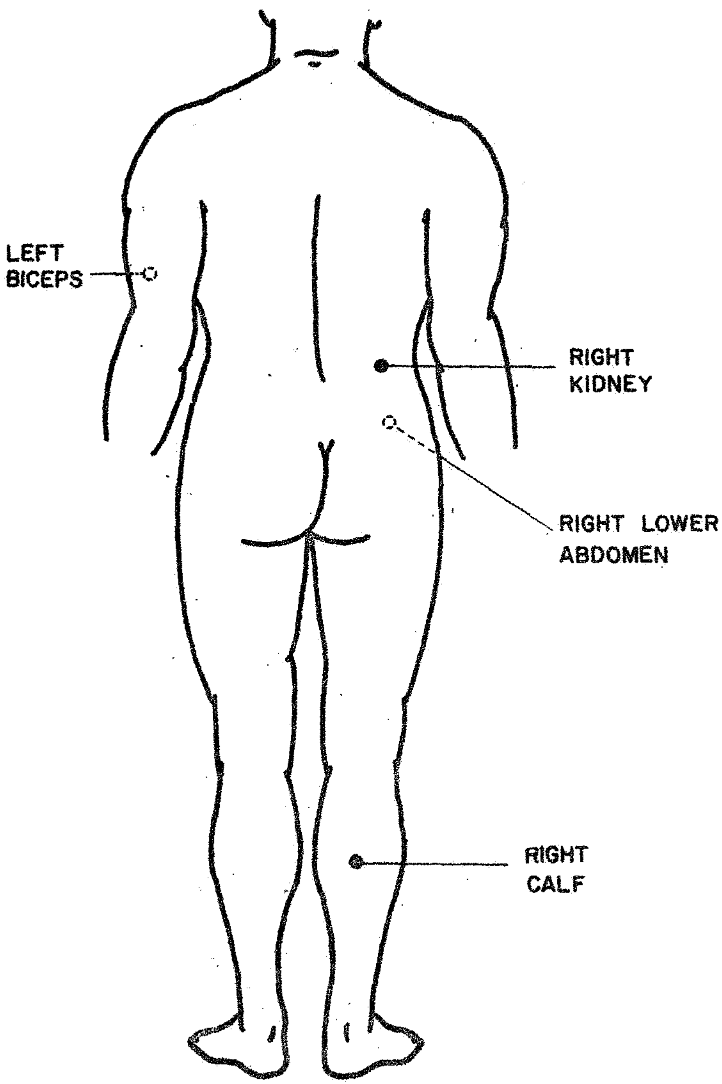
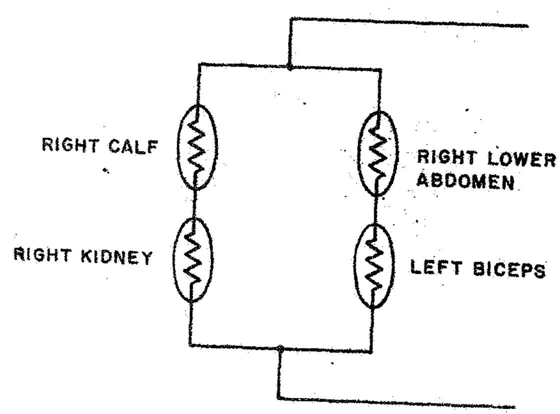


Figure 6 (left). Location of control skin temperature sensors.

Figure 7 (below). Schematic of network for averaging control skin temperatures.



Controller Equation

The performance characteristics of the suit used to effect cooling had to be known for magnitude scaling of the initial mathematical statement (Equation 1) so that the controller could correctly predict T_{wi}. Values for α and β in Equation (1) were calculated for the suit to be used. In addition it was necessary to scale the controller inputs and outputs to be compatible with the voltage control range of the cooler. This scaled expression is given in Equation (4):

$$\frac{T_{wi}}{5} = \frac{T_{wi_0}}{5} - \frac{\alpha}{5\dot{m}c}(H - H_0) - \beta/5(\bar{T}_{cs} - \bar{T}_{cs_0}) \quad (4)$$

where: $\bar{T}_{cs}$ = the average of the control skin temperatures

$\bar{T}_{cs_0}$ = the initial average of the control skin temperatures

α = 6.00

β = 0.72

The values of α and β were subject to revision, since our previous experience had demonstrated that experimental performance of a controller may differ from the results of analog simulation; therefore the controller was designed to afford easy reprogramming of these constants and was not optimized with respect to its mechanization on the computer but left in the form presented in Figure 8.

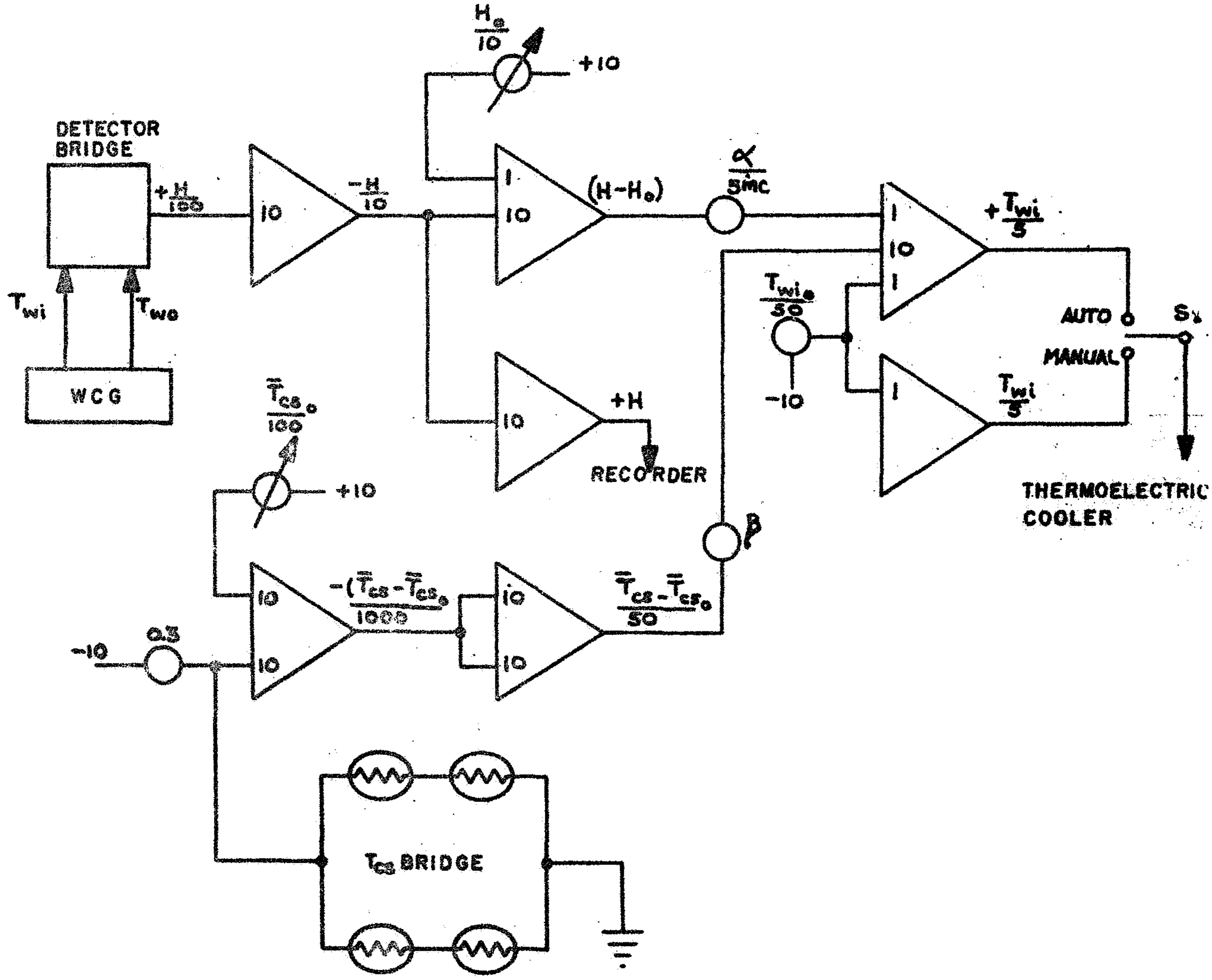


Figure 8. Diagram of experimental ΔT controller constructed with standard analog computer logic elements.

EXPERIMENTS

Laboratory experiments were done with the experimental ΔT controller, first to refine and adjust it, then to see how well it could control metabolic heat removal in various types of work, and finally, in a single long duration experiment, to demonstrate stability and long term accuracy of control.

Equipment, Subjects, and Procedures

Experiments were carried out on a thermally isolated subject wearing a water cooling garment (WCG). Thermal isolation was accomplished by using an insulated and impermeable garment assembly in a temperature kept close to garment temperature. We used $30 \pm 1°C$ in an environmental chamber, and a vapor pressure of 25 ± 3 mm Hg to minimize water loss (cooling) from the respiratory tract.

The WCG was part of a closed water loop containing the suit, a cooler, and a recirculating pump. In the loop the man was the heat source, the cooler the heat sink.

A special cooling garment was used, one made in our laboratory for this type of study. Cooling tubes and skin temperature sensors were incorporated into a single garment which provided the properties of insulation and water impermeability needed to thermally isolate the subject. The basic garment was a 0.25 in. thick unicellular foam neoprene "wet suit" and helmet of the type used by SCUBA divers.

The cooling tubes of 7/32 in. o.d. x 5/32 in. i.d. neoprene rubber were cemented in place on the inner surface of the suit. The total length of the tubes was 150 feet. The Reynolds number for the small tubing was calculated to be about 1900; however, turbulent flow must have been minimal, since the total garment pressure drop (including approximately 4 ft each of pump inlet and outlet lines) was less than 2 psig.

The spaces between the tubes were filled with 1/8 in. thick nylon fabric lined foam neoprene. These inserts increased the total insulation, prevented collapse of the cooling tubes due to pressure applied by the garment against the subject's skin, and minimized crimping across joints during movement. The tubing bulged above this inner layer by 3/32" to make contact with the skin. The total thickness of the garment for the most part was 3/8 in. It is estimated that the total insulation was greater than 2.0 clo. The WCG (including the water cooled helmet) covered approximately 86.4% of the total body surface. The uncooled areas were: the hands, which were covered by rubber surgeon's gloves, and the feet, which were covered by two pairs of wool socks and walking boots, and the face.

Manifolding and delivery tubing (0.25 in. i. d. Tygon) were run on the exterior surface of the garment and insulated from the environment with 1/8 in. thick neoprene foam. The cooling water was distributed from and returned to manifolds containing the dual T_{wi} and T_{wo} sensing thermistors. The distributing and collecting points were located in the lateral waist area. To avoid countercurrent heat exchange, close lying inlet-outlet lines were insulated from one another.

The pump was a directly driven, positive displacement, slung vane unit capable of delivering up to 2.5 lpm flow at 15 psig and 12,600 rpm when driven at full power (28 VAC, 7 amps) by its 0.25 horsepower DC motor. The pump was constructed of a non-corrosive metal, had a single inlet and outlet, and measured 2 in. in diameter by 1-1/8 in. in depth. At the flow rate used, 1.5 lpm, the pump was operated far below its rated capacity. The pump motor also drove a tach generator, the output of which was meter calibrated to set the correct flow rate at various pressures. The pump power supply was variable and regulated to ±0.1%. This provided for smooth pump performance at the pre-set level without further circuitry.

The cooler consisted of three major components: power supply, thermoelectric modules, and controller. Cooling resulted from energizing 12 thermoelectric modules which provided a 3900 Btu/hr heat removal capability. The modules were connected in series and water jackets provided for the hot and cold junctions. Tap water was used as a heat sink at the hot junctions. The cold junction water jacket provided the path through which the suit water passed to be cooled.

The power supply for the cooler operated from a 220 VAC, 10 ampere source, provided an output of 38 VDC at 50 amperes with a maximum ripple of 3% at rated load. The output was smoothed by a tuned series LR (inductive-resistive) network, where the resistive component was the thermoelectric modules. On/off control of the power to these modules was accomplished by silicon controlled rectifiers (SCR's) positioned back to back in the secondary circuit.

The entire water cooling loop was located inside an environmental chamber and close to the subject. It contained a total volume of approximately 1400 cc, including the interconnecting piping (1/4 in. i. d. Tygon) and the WCG. Since the flow rate was 1500 cc/min, the circulation time was less than 1 minute. The system pressure at this flow rate was 3 - 4 psig.

A diagram of the experimental arrangement is shown in Figure 9. The ΔT controller with its two inputs, H and $\bar{T}_{cs}$, were described in the preceding section.

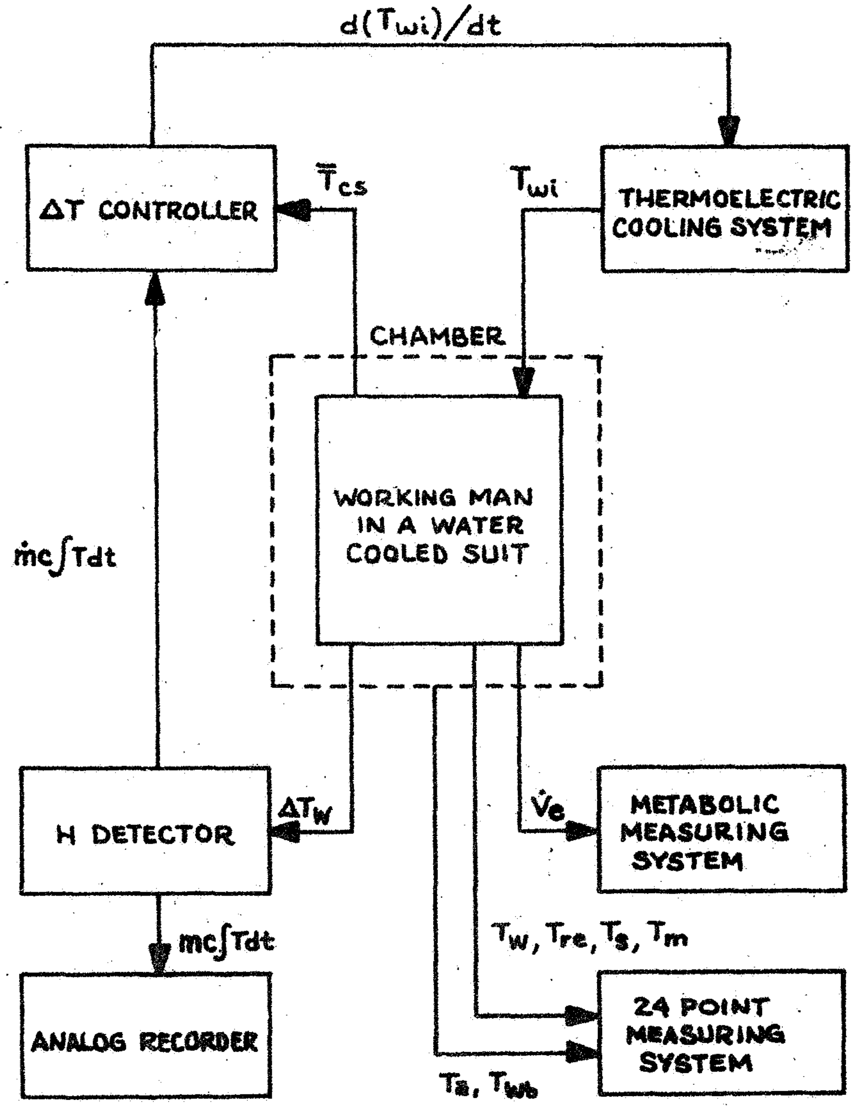


Figure 9. A diagram of the experimental arrangement used for measurements and control.

The physiological measurements observed were as follows:

a. 16 individual skin temperatures (T_s)

b. Mean skin temperature ($\bar{T}_s$)

c. Four control skin temperatures (T_{cs})

d. Rectal temperature (T_{re})

e. Metabolic rate (M)

f. Weight loss

g. Heat removal rate (H)

All temperatures were measured conventionally with thermistors, and logged every two minutes on a 24-point recorder. Metabolic rate was sampled periodically by collection of expired air and gas analysis. Weight loss was measured with an accurate platform balance.

Those components of the system directly involved in measuring controller inputs were given special attention. Pump performance was evaluated so that flow could be determined and maintained constant at the standard rate of 1.5 liters/min; the measured heat removal rate, based on (T_{wo}-T_{wi}), was verified; the effect of the control skin temperatures was estimated by resistive simulation; and the performance of the total system was tested by placing a pseudo man, a resistive heating element, in the water cooling loop where the power applied to the heater was measured and compared to heat sensed by the bridge and removed automatically by the controller and the thermoelectric cooler. This technique validated the flow rate of the coolant and the accuracy of the bridge measurement of heat removal; the results are shown in Figure 10.

Three healthy men, AC, JA, and ST, were used as subjects in the experiments. One was experienced in wearing water cooled garments; the other two were novices. The subjects were similar in physical type and condition. Their personal and anthropometric data are listed below:

Subj.	Age	Height		Nude Weight		Surface Area	Ht/wt ratio
	yrs.	in.	cm.	lbs.	kg.	m^2	
AC	23	71	180	156	71	1.9	.455
JA	36	72	183	146	66	1.85	.493
ST	32	74	188	194	88	2.15	.381

The subjects were clothed in the WCG and remained seated at rest for a minimum of 30 minutes, so that T_{wi}, H, and $\bar{T}_{cs}$ could stabilize, to establish their initial reference levels. When the subject started his activity period, the controller was switched to "automatic" and allowed to control the inlet water temperatures through the remainder of the experimental run. There were no changes made to the controller after a given experiment began. When and if the subject became uncomfortable, the experiment was terminated. The decision to terminate a run was based on subject comments as well as on the physiological measurements being observed. No runs had to be terminated after the controller became properly adjusted.

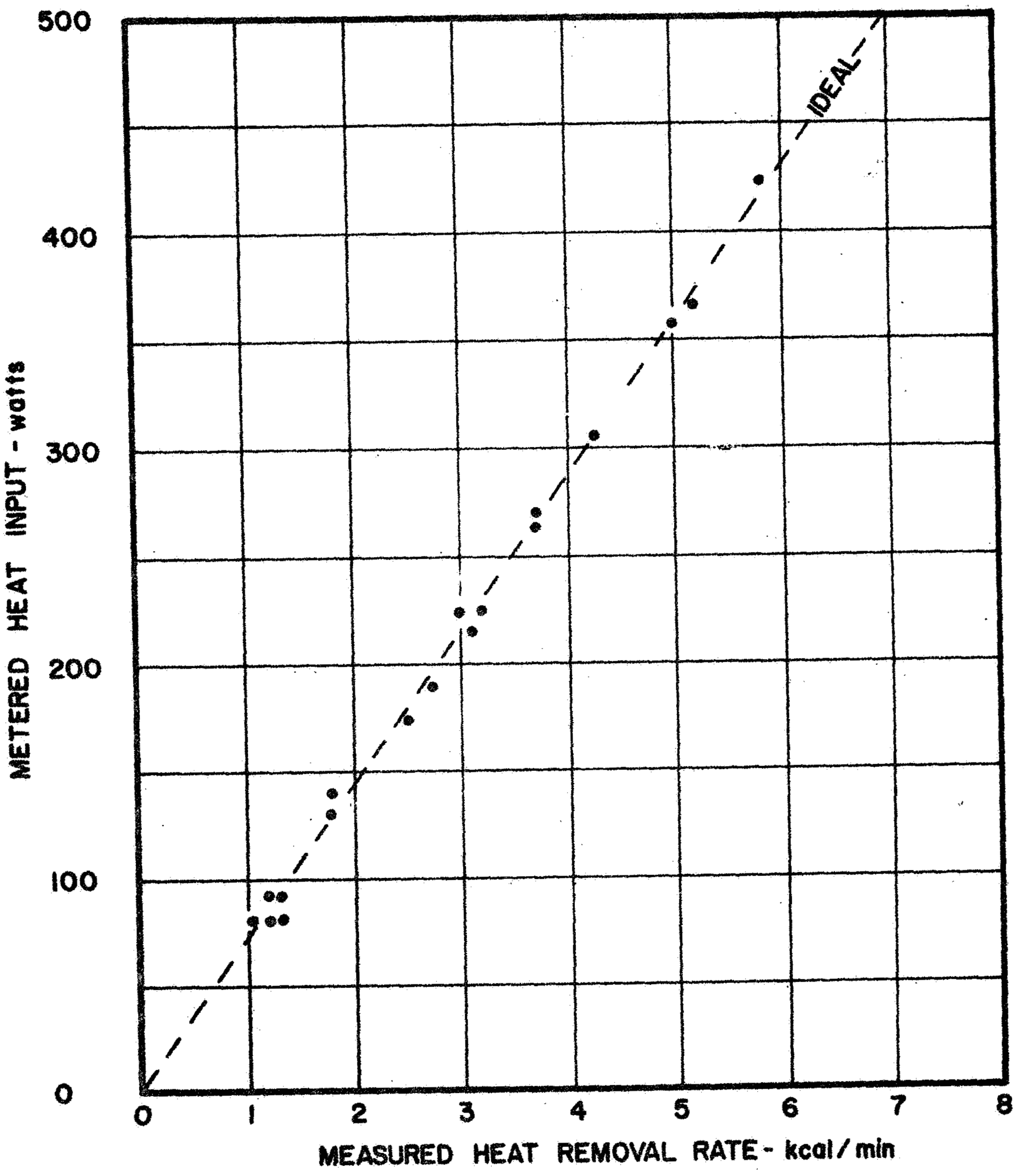
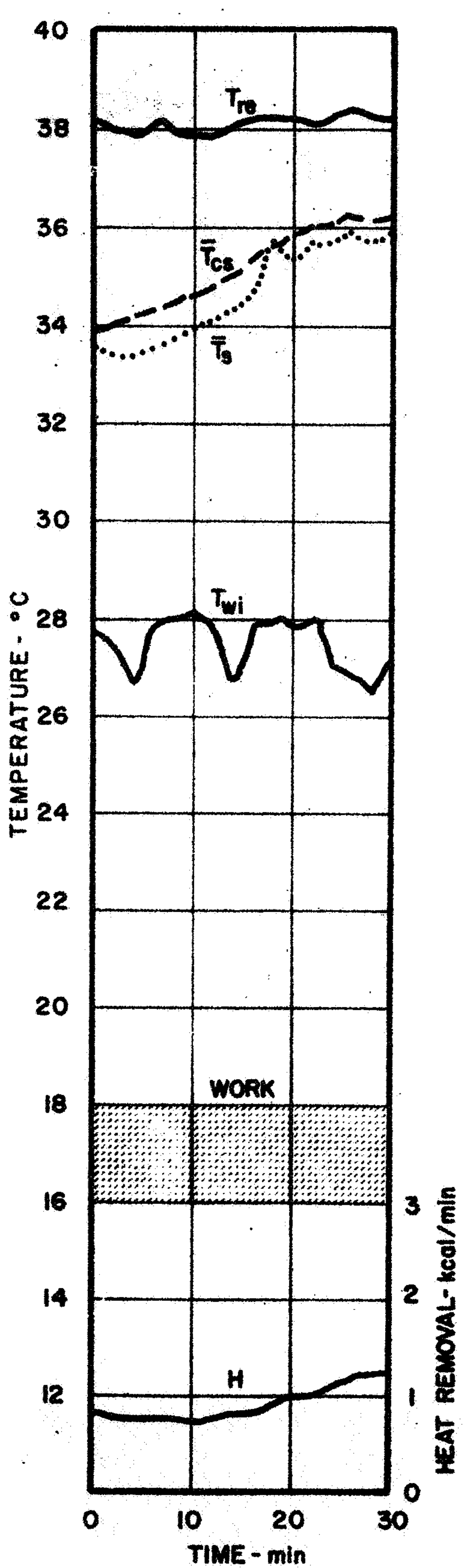


Figure 10. A plot of calibration data for heat input vs. heat removed in the water loop.



Experiments for Adjusting the Controller

It was assumed in designing the ΔT controller that the individual responses of H and $\bar{T}_{cs}$ would be exponential with respect to a change in the level of activity. These variables had to be effectively handled by the contoller; therefore the prime factors in establishing correct control were the adjustments of the constants α and β and the determination of which input should be predominant.

Initial experimentation more clearly defined these control inputs and their function with respect to control logic. The heat removal rate demonstrated various transient responses which were related to this particular WCG and required conditioning by integration to damp out this transient effect. The time constant of integration was equal to 4 times the purge time of the garment proper, or 1 minute. It was then necessary to increase the sensitivity of the controller to H by increasing the value of α to 6.49, thus allowing the resultant response of H to be used as the primary input for the control of T_{wi}. The response of $\bar{T}_{cs}$ was used as a corrective feedback input from the man to adjust the value of T_{wi} so that the desired relationship of T_{wi} to H and $\bar{T}_{cs}$ was established. Contitioning of the $\bar{T}_{cs}$ input was not required, but β was increased to 0.80, thus maintaining the correct input relationships with respect to magnitude. These several complexities will now be described in more detail in their experimental context.

Figure 11. Experimental responses of mean skin temperature, control skin temperature, and heat removal for a man walking 3 mph level in a WCG with the inlet water temperature held at its resting level.

Figure 11 shows the responses of $\bar{T}_s$, $\bar{T}_{cs}$, and H during a 30-minute period when T_{wi} was held at the resting level of 27-28°C while the subject walked on a treatmill at 3 mph (M = 6.5 kcal/min, or 1550 Btu/hr). The magnitudes and rates of change of these responses were analyzed to determine their effect if automatic control had been used. Secondly, the lags between a work step function and a response of $\bar{T}_{cs}$ or H were analyzed to provide some estimate of the performance of a controller using these inputs. During the 30 minutes of work with minimal cooling, the subject reached the limit of voluntary tolerance for heat, and he produced 181 gms of sweat.

A moderate activity level (6.5 kcal/min) was selected for the initial testing of the controller in order to establish the correct values of α and β, the proportionality constants for H and $\bar{T}_{cs}$. The experienced subject was used so that his comments about the control of the cooling could be compared to the measured data and provide information for the controller to be correctly programmed.

The control skin temperatures responded in relationship to the amount of cooling applied with a dual time constant: 1) the response of the skin temperatures as the metabolic heat production changed prior to any effective change in T_{wi}; 2) the rate of change after the cooling potential started to influence the skin temperatures. It was also observed, as before, that the skin temperatures had to be driven lower as subject activity, or more precisely, the level of heat production, increased. The initial rate of change in the skin temperatures appeared to depend primarily on the subject's own physiological response to water cooling; this, coupled with the complex behavior of the skin temperatures, prevented a precise assessment of a value for the time constant of their response. However, it was evident that the combined (dual) time constant was greater than the time constant of T_{wi}.

The heat removal rate as measured in our system responded to two minor transient events which were not related to changes in M: 1) a brief transient response resulting from sudden change in subject position such as standing up or stretching the limbs, this type of activity allowing the heat that had been trapped in the various suit compartments to be dumped; and 2) transients that occurred in the inlet water temperature resulting from on-off power cycling in the thermoelectric cooler. These phenomena caused the control system to oscillate much the same as an underdamped servo; however, it became obvious that the oscillations would not diminish in magnitude due to the interactions of T_{wi} and H and their phase shift of approximately 15 seconds between corresponding events. This phase relationship of T_{wi} to T_{wo} is characteristic of this particular water cooled suit but directly related to the purge time of any given WCG.

It became necessary to make adjustments to the controller response times. Since $\bar{T}_{cs}$ responded to cooling with a time constant greater than that of H, additional damping was ruled out. H did require a damping factor to smooth its rate of change as seen by the controller. The problem encountered here was that as the damping was increased there would result a loss of input sensitivity to what was considered a prime input signal related to changes in activity. To reduce the effects of transients in H on the controller, the response of this input was given a time constant of 1 minute, or four times the purge time of the cooling garment, which was 15 seconds. This conditioned input to the controller seemed to provide the necessary damping of the transients unrelated to M and still respond effectively to changes in metabolic heat production. Until the controller was programmed to handle these input variations from the ideal responses, the weight loss rate ranged from 150 gms/hr to 200 gms/hr as a result of sweating, which exceeded our criterion of good control of not more than 100 gms/hr. The responses of T_{wi} before and after the controller adjustments are shown in Figure 12.

Validation Experiments

Validation of the controller performance after the adjustments were made consisted of experimental tasks considered sufficient to demonstrate how well the controller could handle various levels of metabolic activity. The subjects were asked to do several intermittent and steady work programs which ranged from resting to metabolic levels of approximately 8.5 kcal/min.

The steady work programs were standardized at walking 3 mph level (M = 6.5 to 7.0 kcal/min) for periods of not less than 60 minutes; data from one of these experiments are shown in Figure 13. The curves are quite similar to those obtained in earlier experiments with either manual or $\dot{V}_{O_2}$ control.

Two intermittent work schedules were used: 1) 3 mph at a 5% grade for 5 minute, followed by a 5 minute rest period, with the cycle repeated for 40 minutes, followed by a continuous work period of 3 mph level for 40 minutes, such an experiment being illustrated in Figure 14; and 2) 3 mph level for 20 minutes followed by 3 mph at 3% grade for 30 minutes, and finally 3 mph level for 30 minutes; the results are shown in Figure 15. Again the data were as expected, and control appeared to be good.

Another test, in which the subject was asked to sit quietly at rest for 3.5 hours, demonstrated the stability of the controller; the results are given in Figure 16.

The maximum weight loss observed during these validation runs was 122 gms/hr in the experiment shown in Figure 15. The rate of weight loss was above the desired limit of 100 gms/hr, but it was concluded from the physiological measurements made and from prior experience that the subject was cooled within our definition of correct control.

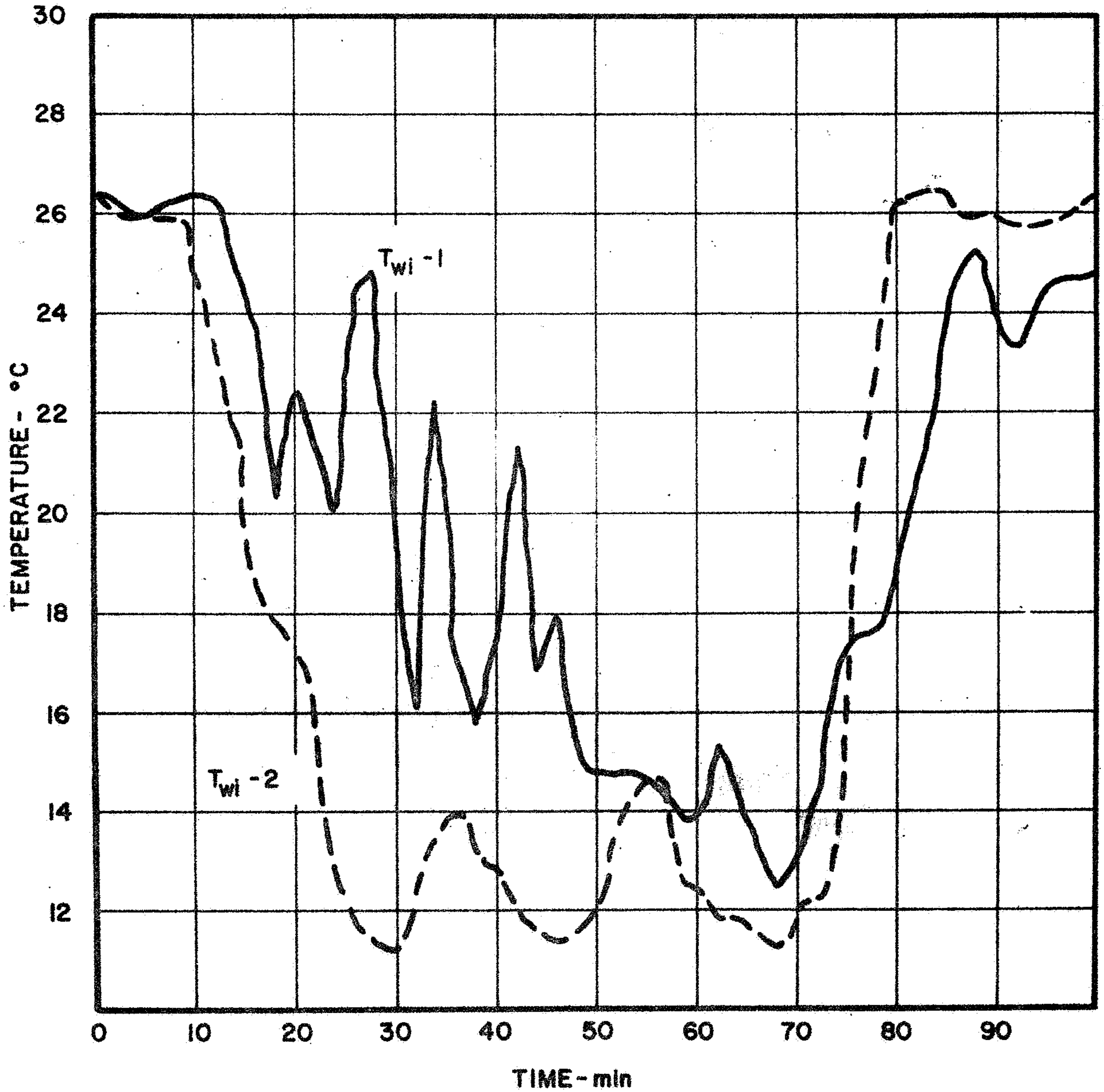


Figure 12. Comparison of experimental responses for inlet water temperature before (T_{wi} - 1) and after (T_{wi} - 2) controller adjustments with a man walking 3 mph level for 1 hour.

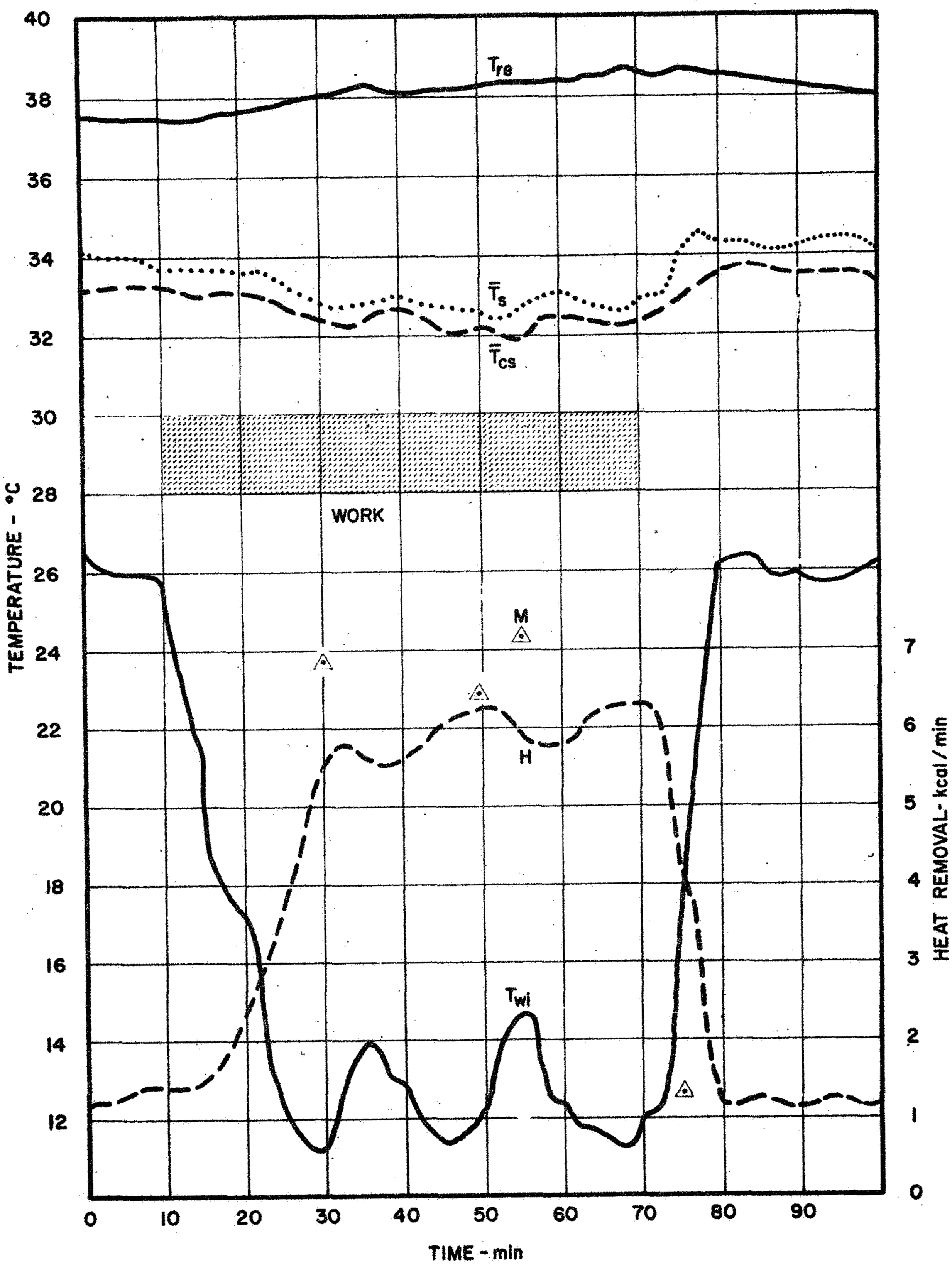


Figure 13. Responses typical of those obtained in automatically controlled experiments in which men worked at 6.5 kcal/min for 1 hour, the work period being shown by the shaded area; H curve is heat extraction from WCG; △ denotes measured metabolic rates; weight loss 110 gms/hr.

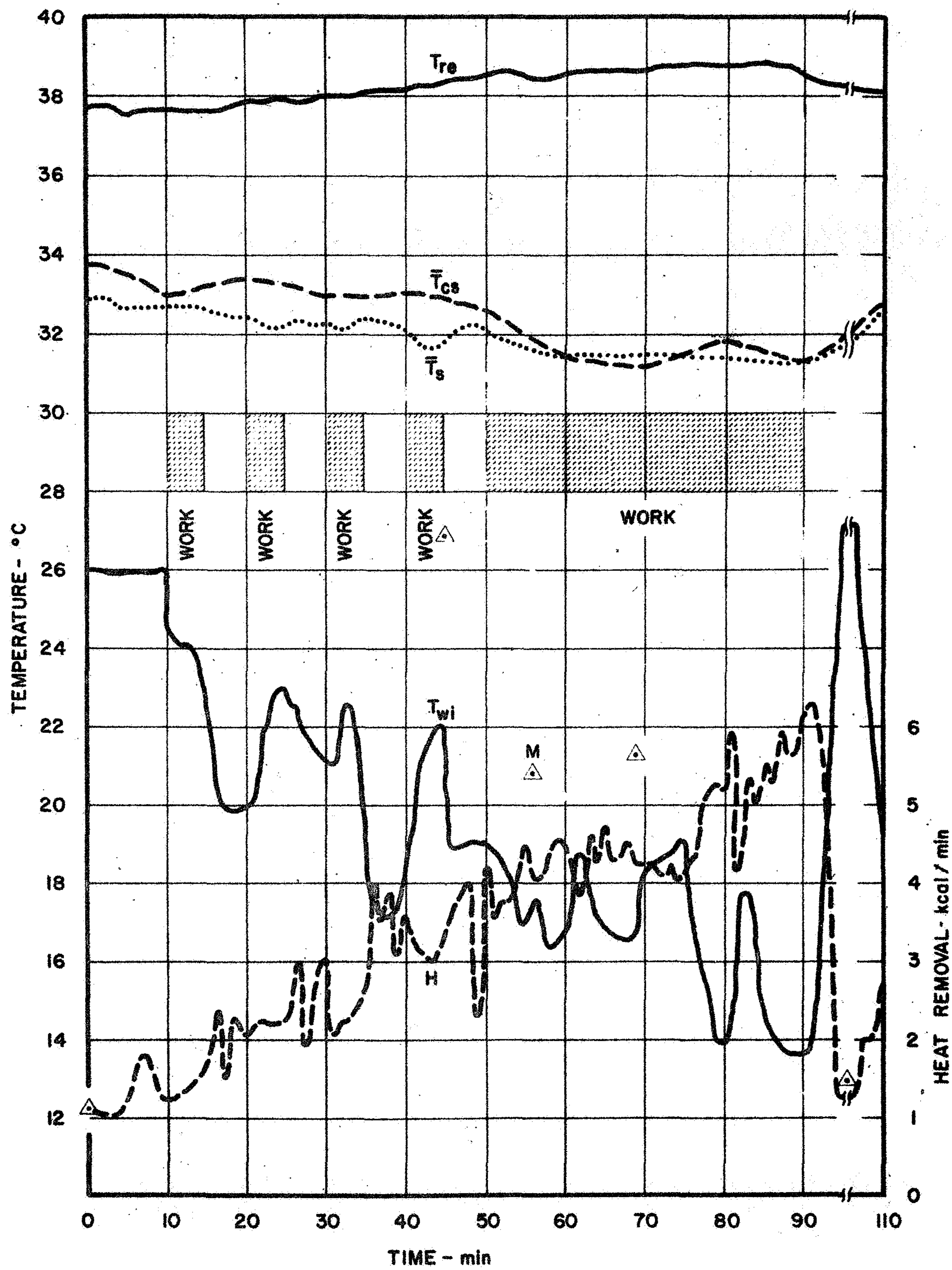


Figure 14. Physiological and cooling responses of automatically controlled intermittent work-rest periods of 8.5 kcal/min followed by steady work at 5.5 kcal/min, as shown by shaded areas; H curve is heat extraction from WCG; △ denotes measured metabolic rates; weight loss 114 gms/hr.

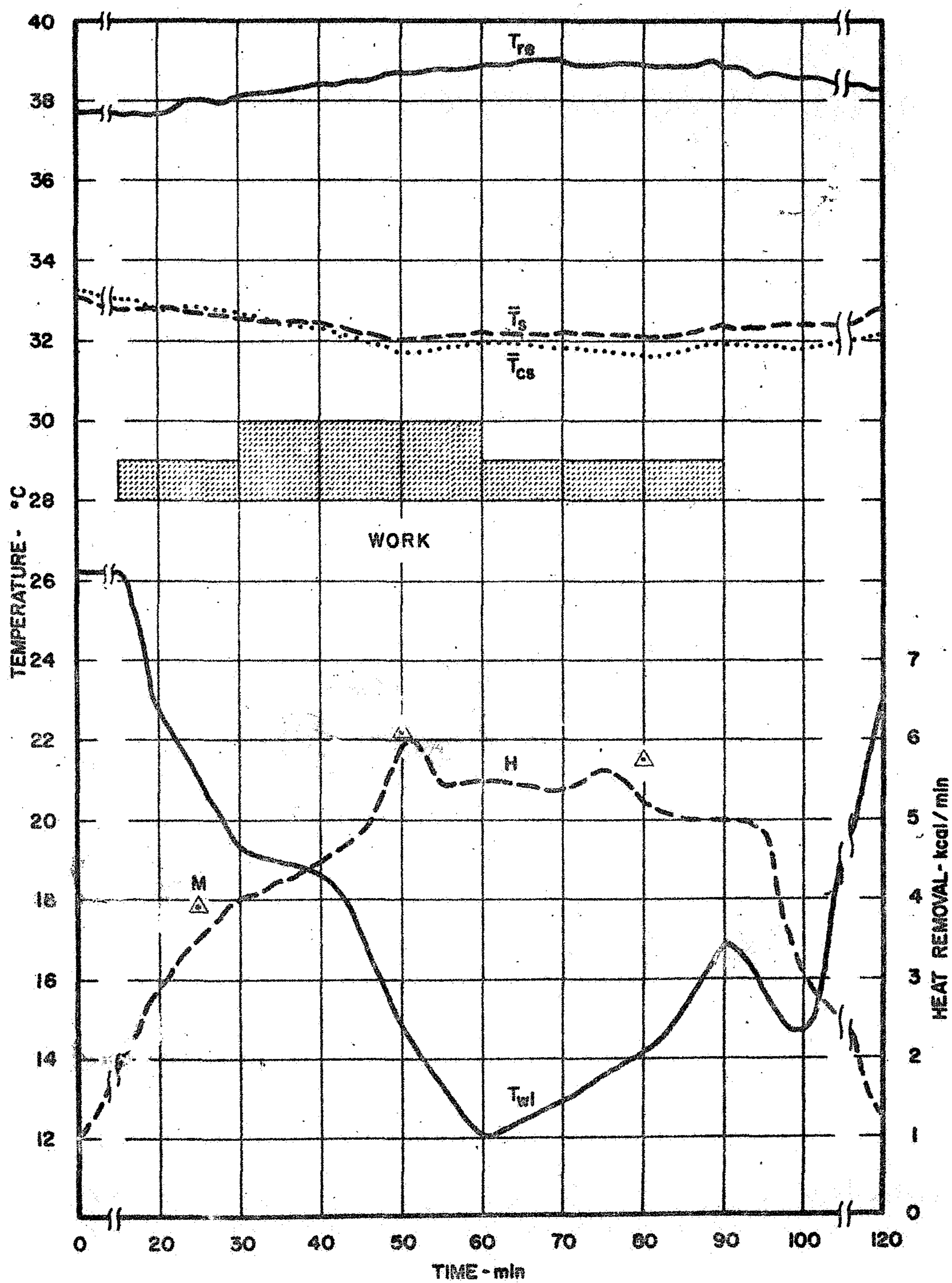


Figure 15. Responses obtained during automatically controlled multiple work periods of 3 mph level; 3 mph at 3% grade; and 3 mph level, as illustrated by the shaded areas; H curve is heat removed from WCG; △ denotes measured metabolic rate; weight loss 122 gms/hr.

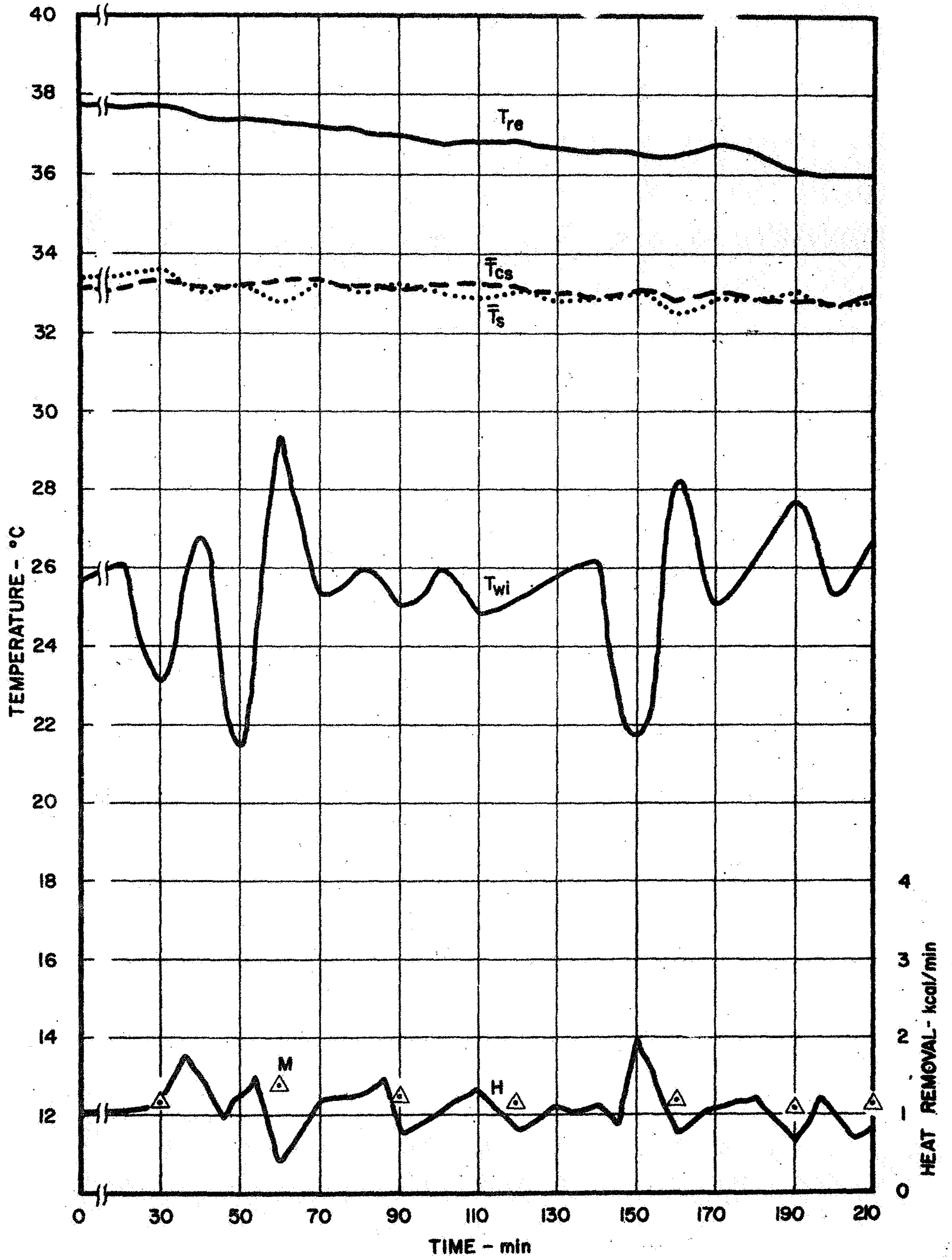


Figure 16. Physiological and cooling responses obtained from an automatically controlled experiment in which a seated man rested for 3.5 hours; H curve is heat extraction from WCG; △ denotes measured metabolic rates; weight loss 52 gms/hr.

The interrelationships of the dependent responses of T_{wi} to the independent responses of $\bar{T}_{cs}$ and H are not clearly definable, since they are directly related to the individual's physiological reactions to water cooling. Although the experiments illustrated in Figures 13 and 14 do provide some insight into the effect that the changes in $\bar{T}_{cs}$ and H or both can have on T_{wi}, the implications of this control technique cannot be fully realized without a more detailed study.

One interesting result clearly evident was the high level of heat removal from the suit for a given activity level. The magnitude of H more closely matched the metabolic rate than it had in our earlier studies. This may become a supplement to the definition of correct control--a condition where H and M approach equality in the quasi-steady state occurring after an hour of activity at a constant level. We suspect that this improved heat extraction resulted from the real time nature of the ΔT controller.

Sixteen Hour Experiment

A final test of the ΔT controller's ability to regulate the heat removal rate from the suit was made during a continuous 16-hour experiment. This test employed a subject who slept, ate two meals, and worked for two periods of 1 hour at 3 mph level. The major data from the 16-hour experiment are plotted in Figure 17. To save space, several long quiet periods when nothing much happened are omitted. There was no significant change in M or H following the two meals, a light breakfast and a supper of steak and salad, which were taken at experiment hour 2 and between hours 12 and 13.

For this test two physiological measurements in addition to the usual ones were taken. In preparation for the experiment, the subject's diurnal cycle was established prior to the run, so that the work periods could be programmed to enable the observers to determine when the rectal temperature had returned to normal after work was concluded. This diurnal curve is shown as one of the curves of Figure 17 and labelled T_{re-d}.

The second additional measurement was thigh muscle temperature (T_m) measured during the experiment with a thermistor probe (Yellow Springs Instrument Co., type 524) mounted in the tip of a 22-gage hypodermic needle 1.5 in. long. These measurements were made during quiet periods, prior to working, during work, and in the recovery period after work. During work periods the subject was asked to stop periodically so that the needle probe could be inserted into his thigh to obtain a temperature reading; during rest the muscle probe was left in the thigh muscle for up to 1 hour, with readings taken periodically. These data are summarized by the T_m curve of Figure 17.

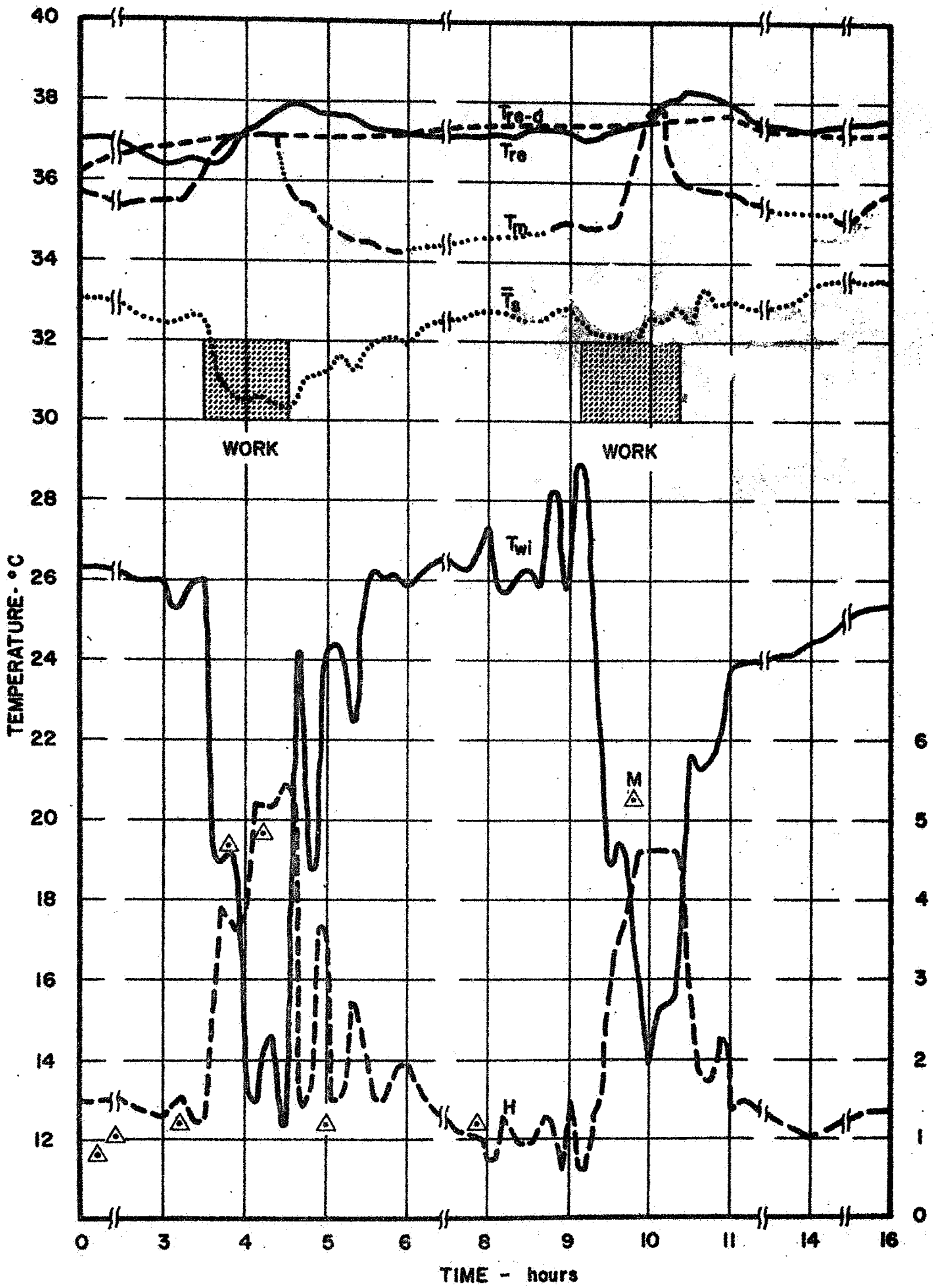


Figure 17. Responses obtained in an automatically controlled 16-hour experiment; work periods are shown by shaded areas; H curve is heat removal from WCG; △ denotes measured metabolic rates; weight loss 32 gms/hr.

T_{re} increased as expected during each work period, rising above this subject's established normal level (the dashed line labelled T_{re-d}). When work was complete, T_{re} fell again to very close to T_{re-d}, which suggests that control was correct and no major quantity of stored heat was retained. Skin temperature levels are consistent with this statement. To complete the heat storage picture, we also had data on T_m, which represents a large part of the body mass. Temperatures in the thigh muscle were also consistent with the idea of no retained heat after an hour of recovery. In fact the muscle temperatures in this experiment were quite different from those reported in the literature for working, uncooled men.

As predicted in our biothermal model of a water cooled man (ref. 7), the muscle temperature increased to levels above the rectal temperature with a short response time of approximately 15 minutes. However, there followed a departure from the expected response. The muscle temperature did not continue to rise and stay higher than the rectal, as shown by Saltin et al. (ref. 3) and others. Instead T_m stayed level at just above 37°C, while T_{re} continued to rise above this point to become higher than T_m. This was observed during both periods of work. This response of T_m can be explained only as a direct effect of water cooling on an active man. A second deviation from the expected was the rapid decrease in these muscle temperatures when work ceased. They appear to have returned to or below their initial temperatures with a response time of approximately 10 minutes, suggesting that when water cooling is applied, the recovery of muscle temperatures is rapid, in contrast to the long slow recovery reported in the literature.

The other temperatures--T_{re}, $\bar{T}_s$, and $\bar{T}_{cs}$--reacted much the same as had been experienced before, except during the first part of the second work period, when a leak occurred in the suit and it had to be opened briefly for repairs. This was, of course, a most critical time with respect to automatic control, and there resulted a delay in the response of the inlet temperature, which never completely returned to the resting level of 26°C. The result was that control of the skin temperatures was lost and their mean was higher than normal at the end of work, therefore preventing the inlet water temperature from rising to its normal level for a resting subject. A slight holdover in H was also observed.

The 16-hour experiment was considered a valid test of the controller, since long term stability and control for different types of subject activity were established. The weight loss for the 16-hour period was only 32 gms/hr, the subject was comfortable throughout, and H and M were very nearly equal during the entire period.

These experiments tested our ΔT concept of control and met our basic criterion of minimal sweating and no gross or prolonged chilling. Subjective comments by the experienced subject supported the notion that automatic control is the preferred method of regulating water cooling and removing the metabolic heat of a thermally isolated man.

DISCUSSION

The developmental procedure, analysis, and validation specific to automatic control of water cooling using the concept of differential temperatures related to metabolic heat production are particular to our water cooling garment and environmental conditions. However, adaptation of this experimental ΔT controller to various types of WCG's should be possible if the performance characteristics of the suit are known.

Our experiments focused on what might be considered normal activity levels for water cooled men, with emphasis placed on stability and performance of the controller, so that variations in physiological responses would not result in undesirable cumulative effects.

The control system performed well within the desired design limits, even though certain parameters were based on a limited knowledge of complex biological responses. Linearization and manipulation of control information did not appear to derate the performance of the model controller in predicting physiological responses nor the ability of the ΔT controller to control with reasonable accuracy. The controller was not tested at high metabolic rates due to cooling limitations which developed in our thermoelectric cooler; however, based on previous experience, it was felt that had the cooler been capable of driving T_{wi} lower, the ΔT controller could have handled higher rates. In the previous studies with the same cooling garment, H as high as 9 kcal/min (2160 Btu/hr) had been achieved, and this together with the losses and external work meant that at least 10 kcal/min in heat production could be dissipated and a steady thermal state maintained.

Refinement of the present experimental controller with respect to hardware, adaptability, and performance would increase its usefulness as a control system. For example: 1) investigative studies in the area of sensing skin temperatures might result in a further optimization of the number and type of measurements required; 2) extensive testing with various types of water cooled garments would provide performance data that could lead to development of proportionalized control constants such that a single adjustment would adapt the controller to an individual or to a given WCG; and 3) improved instrumentation might make it possible to measure the heat removal rate without having to modify its natural response. These refinements and possibly others would result in a much improved control system.

Comparison of the ΔT controller with the $\dot{V}_{O_2}$ controller reveals several important advantages of the ΔT controller concept:

1. The $\dot{V}_{O_2}$ controller used a continuous measurement of oxygen consumption as its input, a measuring technique which presents operational problems in space flight, whereas the ΔT controller used simple and reliable temperature probes to provide control input information;
2. Control from $\dot{V}_{O_2}$ was open loop with no corrective feedback, whereas the closed loop operation of the ΔT controller provided information relating to the subject's physiological state as feedback to prevent thermal stress;
3. programmed control (no feedback) based on $\dot{V}_{O_2}$ measurements does not adjust for individual variations in a subject's response to water cooling, but the ΔT concept resulted in some adaptation to these physiological variations.

The ΔT controller did not provide a smoothly driven T_{wi} response as was the case with the $\dot{V}_{O_2}$ approach; however, it was postulated that the response of T_{wi} when controlled by the new controller was more closely related to the need for heat removal.

Further, the new ΔT controller gave even better heat extraction, that is, H nearly equal to M, and heat storage appeared to be minimal. The best evidence for this was in the experiment lasting 16 hours, as discussed above. In all experiments 90-95% of M appeared in H plus evaporative heat loss (plus external work if the subject walked uphill.) This comes tantalizingly close to complete heat balance. We speculate that the high heat extraction and the good stability of long term control result from the continuously adjusted real time nature of the controller and from the corrective information supplied through the $\bar{T}_{cs}$ input.

Adaptation of our controller to additional types of water cooled garments would require a thorough knowledge of the garment and its performance characteristics, such as: the determination of the proper initial value for T_{wi}; the relationship of metabolic heat appearing in the coolant to the level of metabolic activity; maximum heat removal capability; and the responsive characteristics of the skin temperatures selected for control. These definite relationships in conjunction with the control logic should provide the necessary tools for adaptation.

One aspect of the experimental data observed is the possibility of a deeper insight into the physiological responses resulting from water cooling, such as the measurement of thigh muscle temperatures during quiet rest, work, and recovery after work, which will be of great value in improving our biothermal model. It is clear that a cooled man is different from an uncooled man, and with correct control heat storage is minimized.

The increase in the heat removal rate with respect to heat production seems to indicate that real-time control is more efficient than other types of predictatory control approaches. The important result of this control concept was that its performance was reasonably predictable and as good as, if not better than, our earlier efforts at continuous control.

CONCLUSIONS

1. Automatic control of the heat removal in water cooled suits is feasible and has been experimentally demonstrated.

2. Automatic control can prevent gross sweating or chilling and maintain a comfortable environment for the subject.

3. Physiological responses which are directly related to metabolic heat production during water cooling may be used to provide control.

4. Long term stability and reasonable accuracy result from closed loop or feedback control concepts.

5. Development and refinement of control inputs are theoretically possible.

6. T_{wi} can be related to various biological measurements associated with water cooling and the removal of metabolic heat production by simple linear mathematical statements.

7. High rates of heat removal are possible when automatic control is activated and driven by direct physiological responses.

APPENDIX

List of Symbols and Appreviations

Symbol	Definition	Units
α	proportionality constant for H	----
β	proportionality constant for $\bar{T}_s$	----
ϕ	proportionality constant for M, RM	----
τ	time constant	min
c	specific heat	kcal/kg-°C
H	heat removal rate	kcal/min
H_0	initial heat removal rate	kcal/min
M	metabolic rate	kcal/min
$\dot{m}$	mass transfer rate	kg/min
T	temperature	°C
T_a	dry bulb temperature	°C
T_{cs}	skin temperature used for control	°C
$\bar{T}_{cs}$	average of control skin temperatures	°C
$\bar{T}_{cs_0}$	initial control skin temperature	°C
T_l	model leg compartment temperature	°C
T_m	thigh muscle temperature	°C
T_{re}	rectal temperature	°C
T_{re-d}	diurnally varying rectal temperature	°C

Symbol	Definition	Units
T_s	skin temperature	°C
$\bar{T}_s$	mean skin temperature	°C
$\bar{T}_{s_0}$	initial mean skin temperature	°C
T_w	water temperature	°C
T_{wb}	wet bulb temperature	°C
T_{wi}	inlet water temperature	°C
T_{wi_0}	initial inlet water temperature	°C
T_{wo}	outlet water temperature	°C
RM	resting metabolic rate	kcal/min
$\dot{V}_e$	respiratory minute volume	liters/min
$\dot{V}_{O_2}$	oxygen consumption	liters/min

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